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SOUND PROPAGATION
LOSS PREDICTION FOR 100 Hz RECEIVER

by

Walter Lewis Glenn, Jr.

UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

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SOUND PROPAGATION

LOSS PREDICTION FOR 100 Hz RECEIVER

by

Walter Lewis Glenn, Jr.
Lieutenant, United States Navy
B.S., United States Naval Academy, 1962

[redacted]

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
June 1968

NPS Archive
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Glenn, W.
~~Thesis G4594 c.1~~

ABSTRACT

This paper reports an attempt to simplify for ease in field use the complex numerical model for sound propagation loss prediction developed by Dr. C. S. Clay, Captain P. M. Wolff, and Dr. P. R. Tatro (LCDR, USN). Due to time required for communications and computation, the present results of this model are not available for immediate use by the operator in the field.

This computerized model was used to analyze propagation loss for temperature profiles with sea surface temperature varying between 10C and 25C and variation in mixed layer depth from the surface to 300 meters. From these data formulas and graphs were developed to predict convergence zone range, width, and intensity and the 100-decibel propagation loss range. These results are intended for operational use by field personnel.

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ACKNOWLEDGMENTS

Despite his extremely busy schedule as a research oceanographer at the FNWF, Dr. P. R. Tatro (LCDR, USN) has taken valuable time to encourage, question, teach, and move me toward completion of this study. A. L. Seeke (AG1, USN) at the FNWF has also given his time and used his considerable experience in environmental conditions to help ensure that the initial model corresponds closely to actual water conditions. I extend my sincere appreciation to them and others at the FNWF for their help on this project.

To Dr. Glenn H. Jung, Professor of Oceanography at the Naval Postgraduate School, the author wishes to express sincere thanks for his guidance through the myriad sidetracks to ensure minimum wasted time and maximum useful effort expended.

CHAPTER I

INTRODUCTION

A numerical model for calculating sound propagation loss from a source at a given depth to a receiver at a given depth in the sea is presently employed at the Fleet Numerical Weather Facility, (FNWF), Monterey, California. This model is used to provide tactical information to operational naval forces and for other strategic uses. However, due to turnaround time required for computation and communications, the results are not available for immediate operational usage in the field.

This model was developed and adapted for computers in November 1967 by C. S. Clay, P. M. Wolff, and P. R. Tatro. Recent comparisons of predicted values with values obtained in controlled field studies have shown the model to produce excellent results. The Bolt, Beranek, and Newman (1966) report gave finer detail on sound loss, but the FNWF model compared very favorably over the entire sound propagation loss path.

Having worked operationally in this field as ASW officer on the USS VESOLE (DDR-878) and on the USS RICHARD E. BYRD (DDG-23), the author has firsthand experience in the many frustrations encountered in coping with sound detection in the sea. This frustration is shared by other operators as noted by Glennon (1965). By using the results of the FNWF model as a standard, it is intended to develope some simple equations and graphical displays for use by the operator directly in the field.

This work is concentrated on the convergence zone range, width, and intensity for convergence zones one, two, and three. Data and graphs

are also presented for the 100-decibel propagation loss range. Additional runs would be required to utilize the 100-decibel data in a more meaningful manner.

This paper is divided into three principal parts. The first part is an explanation of the basic features of the sound propagation loss model used to develop the data. Since the model description has not been published, this information is derived from personal consultation with Dr. P. R. Tatro and Dr. C. S. Clay.

The second part will include an approach to obtaining data for reduction, and a description of the methods used for reducing the data obtained. The fine atlas of Pacific water conditions developed by Muromtsev (1963) has been of considerable help in developing this ocean model.

The last section will be the display of graphical results and the equations developed for operational use. These calculations will be shown with the realization that some differences may exist between these results and actual conditions in the field. It is intended that the model predictions will be accurate enough to be of some operational use.

CHAPTER II

SOUND PROPAGATION LOSS MODEL

The sound propagation loss model was developed to calculate the transmission loss for low frequency sound in the world oceans. Losses developed in the model depend on sound velocity profile, depth, sea state, sound frequency, and the type of ocean bottom present. These parameters in turn are dependent on such variables as sea surface temperature, mixed layer depth, temperature profile, source and receiver depths, bottom roughness, and salinity. The model was developed in such a manner that these variables may be changed independently as demanded by environmental conditions or operational need. Anderson and Lesser (1959) indicate some effects of these changes.

The procedures in the construction of this model have been used for experimental analysis by various research facilities. The model combines these procedures with modern high speed computers to provide products for sonar systems on a worldwide scale.

Sound loss in the model is assumed to occur over ten different types of paths in the ocean. These paths are:

(1) First bottom bounce path up

(2) First bottom bounce path down

(3) Second bottom bounce path up

(4) Second bottom bounce path down

(5) Convergence zone path up

(6) Convergence zone path down

(7) Direct path up

(8) Direct path down

(9) Surface duct path

(10) Subsurface duct path.

Urick (1964) and Anderson and Pedersen (1965) have further amplifying details on these transmission paths in the ocean.

For further clarification of these paths, a graphical display of each path is shown in Figures 1, 2, 3, and 4.

Sound energy is traced along ray paths for every two degrees from horizontal (0 degrees) to nearly vertical (88 degrees). Sound propagation loss is computed and stored in the computer at 1000 yard (0.5 nautical mile) increments for ranges extending from 1000 yards to 250,000 yards. Since these are one-way transmission losses, they should be doubled if used with active sonar systems.

Sound energy loss contributions to the total energy loss along the various paths are calculated separately: the total loss is the ratio of total energy available via the various paths to an initial energy assumed to be unity. This is conventionally expressed as a logarithmic unit, the decibel. These components are independent of each other and the method for obtaining each component will be covered in the following paragraphs.

<u>Losses Along Direct Path, Convergence Zone and Bottom Reflected Paths</u>

Losses via direct path, convergence zone, and bottom bounce are calculated by use of the following equation:

$$\text{Loss} = 10 \log \left(\frac{R}{\cos \theta_i}\right) + 10 \log L + aR + N_b + N_s \tag{1}$$

where

R = range from source to receiver

θ_i = angle of ray leaving source

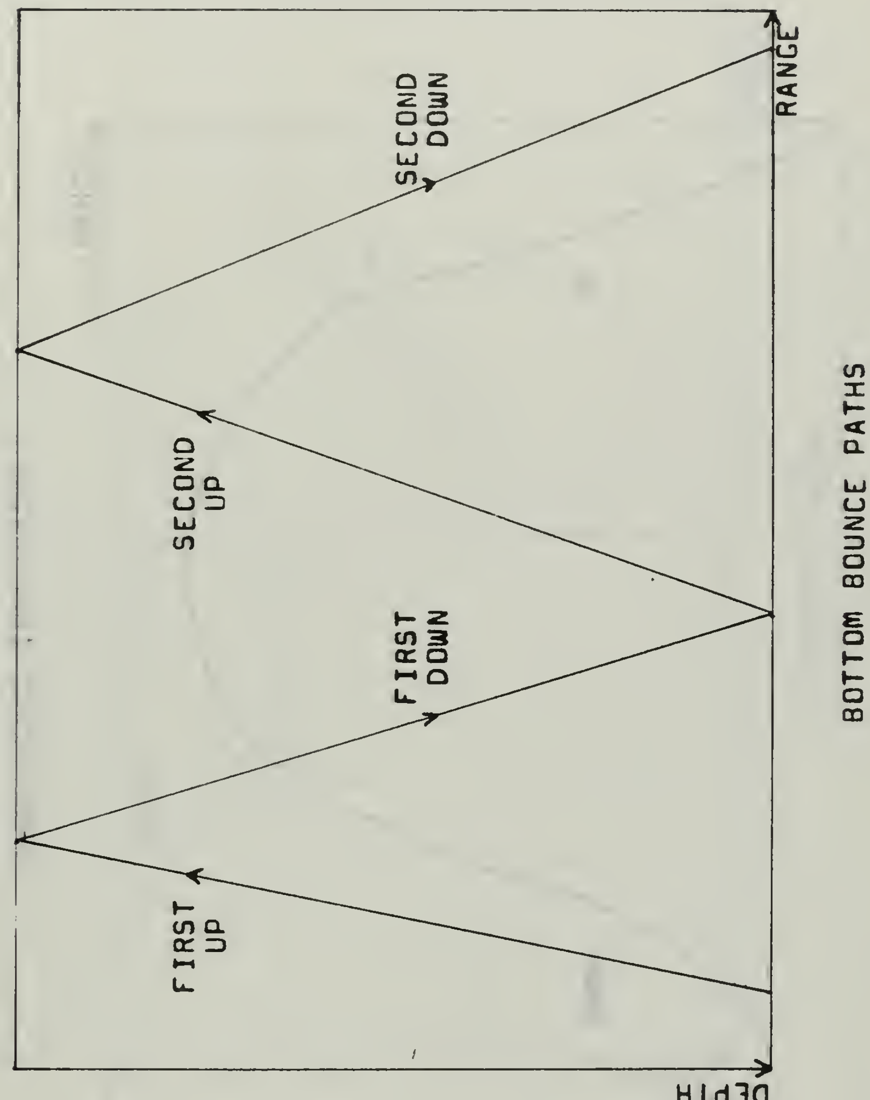

FIRST UP
FIRST DOWN
SECOND UP
SECOND DOWN
RANGE
DEPTH
BOTTOM BOUNCE PATHS

Figure 1

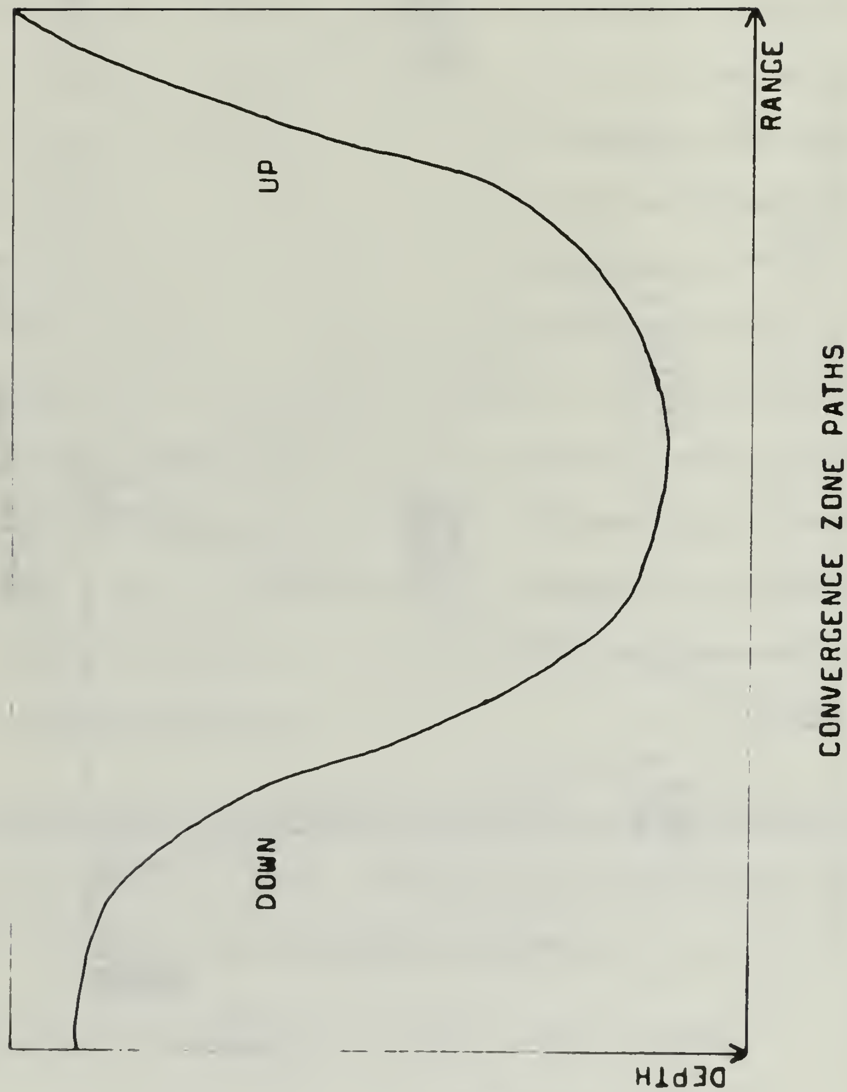


Figure 2

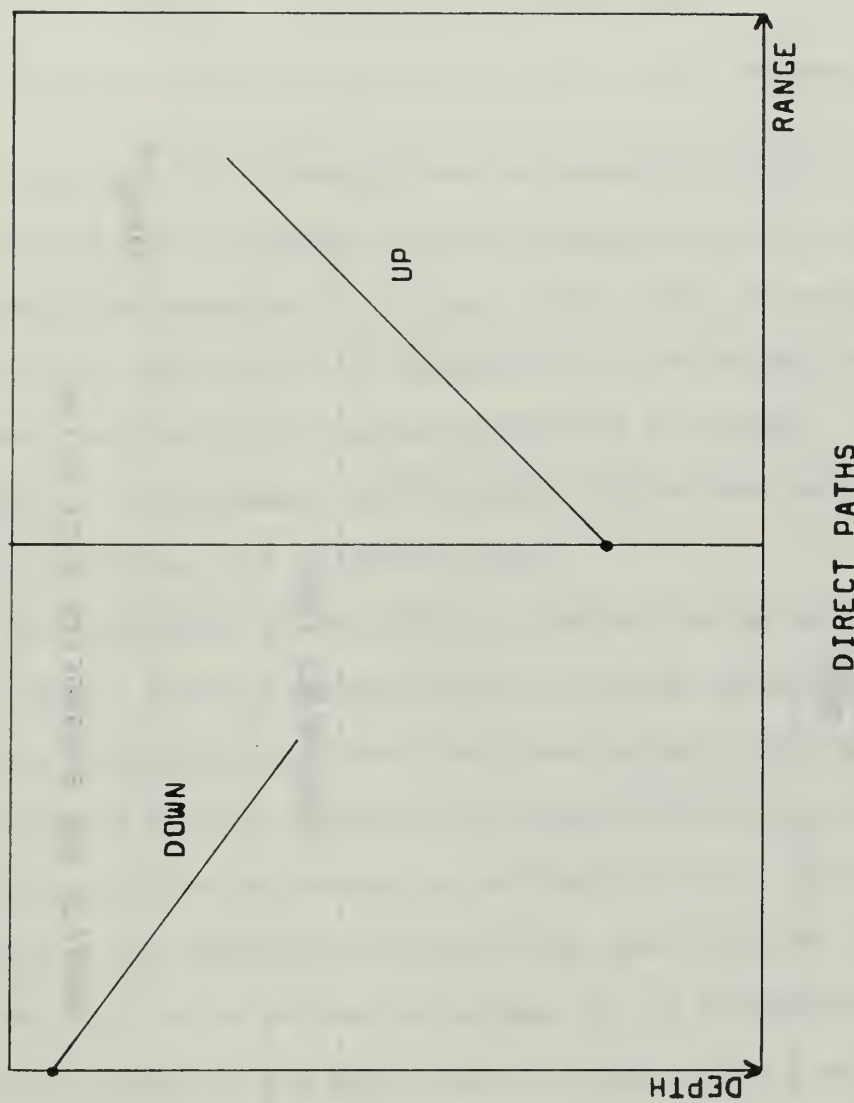
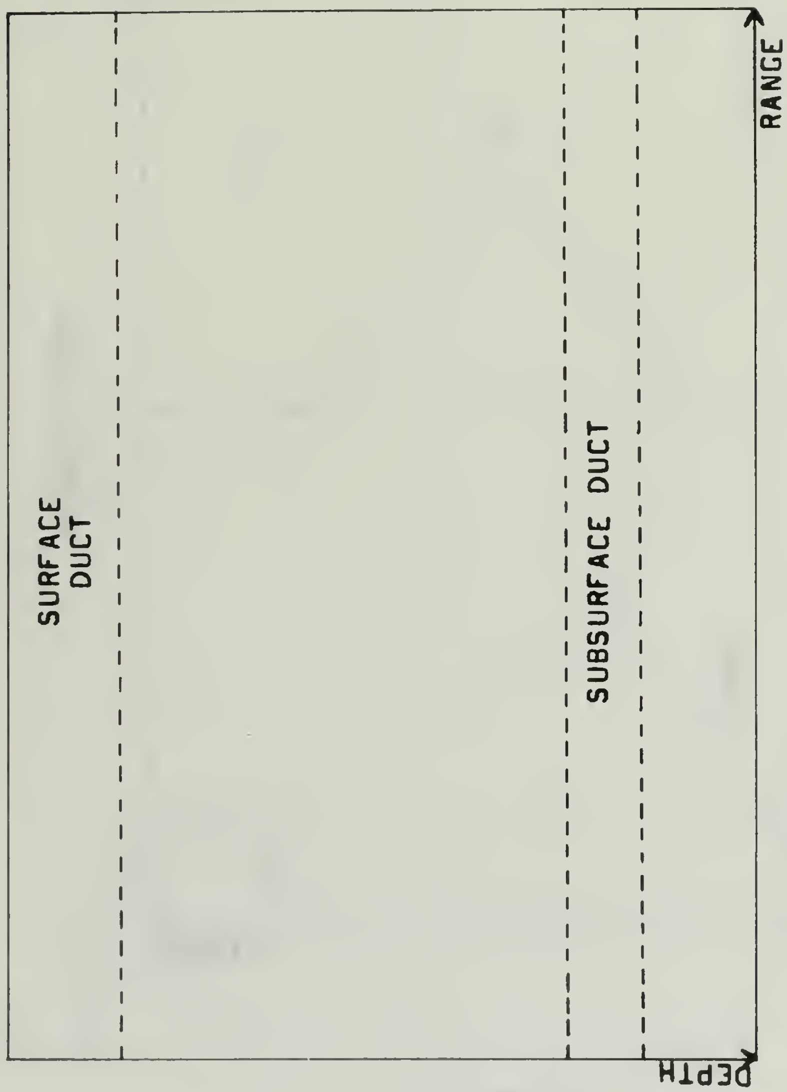


Figure 3



SURFACE AND SUBSURFACE DUCT PATHS

Figure 4

L = vertical distance between spreading rays in the range-depth plane

a = absorption coefficient

N_b = loss due to reflection from bottom

N_s = loss due to reflection from ocean surface

$10 \log (\frac{R}{\cos \theta_i})$ = cylindrical spreading loss

$10 \log L$ = differential spreading loss in the range-depth plane.

Since most of the ocean bottom is considered rough for low frequency sound, this roughness has been accounted for in the model by the term N_b in equation (1). Using a varied scale of roughness from one to five, where one is the smoothest type bottom and five the roughest, the loss due to bottom variability is computed. The calculation of the roughness has been made using seismic date, physiographic provinces, and bathymetric data.

The composition of the bottom is included in the model through N_b by using a given propagation loss for certain materials. At present only two designations are used, and these factors differentiate between the "fast" or low loss bottom of the Atlantic Ocean and the "slow" or higher loss bottom encountered in the Pacific Ocean. N_b is also a function of the angle which the sound ray makes with the ocean bottom.

The loss due to surface reflection, N_s, is a function of sea state, the angle the ray makes with the ocean surface, and the frequency of the sound traveling through the water. The cylindrical spreading loss and the differential spreading loss combine to give the geometric spreading loss of the signal.

Bottom reflected energy is calculated using equation (1) out through only two bottom bounces. Energy loss after the second bounce is extrapolated using:

$$\text{LOSS} = \text{Constant} + 10 \log R + aR + AB \cdot R \tag{2}$$

$$\text{Constant} = L - (10 \log R_1 + aR_1)$$

L = sound energy at end of second bottom bounce

R_1 = range to end of second bottom bounce zone

R = total range

$$AB = \frac{L_{0.4}}{D_c}$$

$L_{0.4}$ = energy loss at $\theta_b = 0.4$ radians

θ_b = angle incident ray makes with bottom

D_c = range where no more rays exist that have hit the bottom only once, or twice for first or second bottom bounce respectively.

<u>Surface Duct and Subsurface Duct Losses</u>

Surface duct and subsurface duct losses are treated using an approximation to a normal mode solution. The equation used for this determination is

$$\frac{I}{I_o} = \frac{N\Delta\theta}{RZ_o} e^{-\beta\frac{\sqrt{x_o\gamma}}{Z_o} R} e^{-\alpha R} \tag{3}$$

$$\text{Loss} = -10 \log \frac{I}{I_o}$$

where

R = range from source to receiver

I_o = initial intensity of signal

$\Delta\theta$ = angle of energy trapped in a duct of depth Z

x_o = half cycle distance

γ = wavelength of sound

α = absorption coefficient

Z_o = the vertical extent of either the surface or the subsurface duct

β and N = empirical constants.

β and N may be altered as verification data from field studies become available, which permits the model to be "tuned" without difficulty.

CHAPTER III

FIELD PREDICTION APPROACH

With this model available for sound loss prediction, the problem was to determine the variables to be used to produce information satisfactory for field prediction. James (1966) and Urick (1967) offer guidance in determining the best group of variables.

The parameters available included sea surface temperature, mixed layer depth, temperature gradient, sea state, source depth, receiver depth, frequency, bottom depth, bottom type and roughness, and salinity. Each parameter may be varied independently to determine the effects it has on the total propagation loss in sound transmission through the sea, which is indicated in matrix form in Figure 6. An interpretation of the matrix is given in Figure 5.

The sample output in Figure 6 gives the propagation loss from the source to the receiver for a 4000-meter (13,123 feet) water depth, zero mixed layer depth, and 15C sea surface temperature. The first, second, and third convergence zones are underlined and can be clearly seen in the particular example.

Sea surface temperature, mixed layer depth, and temperature gradient have a strong influence on sound propagation and are easily determined operationally at the scene; therefore, these variables were selected for extensive use in this study. The selection of particular ranges of values to be used will be discussed in detail below.

Primary interest was centered on convergence zones which are caused by the partial focusing of refracted ray paths and generally require a deep sound channel and large ocean depth. Thus, variation in bottom depth over a limited range was included. The focusing

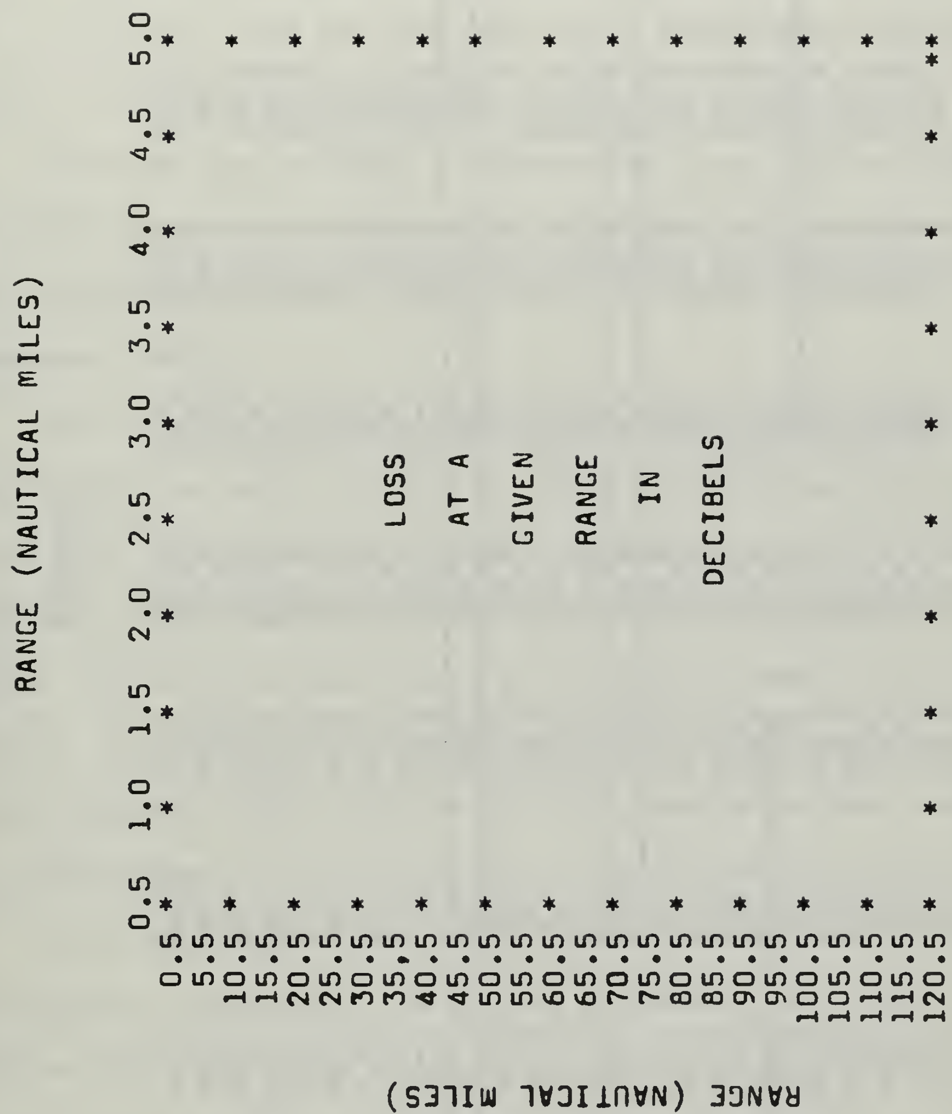

RANGE (NAUTICAL MILES)
0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
LOSS AT A GIVEN RANGE IN DECIBELS
0.5 5.5 10.5 15.5 20.5 25.5 30.5 35.5 40.5 45.5 50.5 55.5 60.5 65.5 70.5 75.5 80.5 85.5 90.5 95.5 100.5 105.5 110.5 115.5 120.5
RANGE (NAUTICAL MILES)

Figure 5

FAMILY 1 MLD 000 150 SOURCE AT 100 FT. RECEIVER AT 90 FT.
DEPTH 13123 FT. ROUGHNESS 4. OCEAN = P. FREQ = .10 KHZ. SEA STATE 4.

.5	57.1	90.1	90.3	90.7	91.1	91.5	92.0	92.5	93.0	93.4
5.5	93.9	94.4	94.9	95.3	95.8	96.2	96.6	97.0	97.4	97.8
10.5	98.2	98.6	98.9	99.3	99.6	100.0	100.3	100.7	101.0	101.3
15.5	101.6	102.0	102.4	102.7	103.0	103.4	103.7	103.7	103.8	103.9
20.5	104.0	104.1	104.2	104.3	104.4	81.7	74.8	76.3	83.6	88.1
25.5	89.9	91.6	93.1	95.3	123.6	123.8	124.0	124.1	124.3	124.5
30.5	124.6	124.8	124.9	127.9	128.0	128.1	128.1	128.2	128.3	128.3
35.5	128.4	128.5	128.5	128.6	128.6	128.7	128.7	128.8	128.9	128.9
40.5	129.0	129.0	129.1	129.1	129.2	129.2	129.3	129.3	129.4	129.4
45.5	129.5	129.5	83.2	81.2	81.7	82.7	85.8	89.3	91.1	92.3
50.5	93.3	94.1	94.9	95.7	96.5	97.4	98.0	100.0	188.6	189.1
55.5	189.6	190.0	190.5	190.9	191.4	191.8	192.2	192.5	192.9	193.2
60.5	193.6	193.9	194.1	194.4	194.7	194.9	195.1	195.3	195.5	195.6
65.5	195.8	195.9	196.0	196.1	196.2	196.3	196.4	196.4	91.5	86.4
70.5	84.9	85.3	85.6	86.2	87.6	90.1	93.9	96.1	97.6	98.7
75.5	99.6	100.3	100.6	99.7	98.9	98.1	97.6	97.2	96.7	96.1
80.5	95.6	97.4	196.9	196.9	196.9	196.9	196.9	196.9	196.9	197.0
85.5	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0
90.5	197.0	197.0	197.0	197.0	197.0	90.2	88.6	87.7	87.9	88.1
95.5	88.3	88.8	90.0	94.2	197.0	197.0	197.0	197.0	197.0	197.0
100.5	197.0	197.0	197.0	105.8	104.4	102.0	102.4	105.5	107.0	197.0
105.5	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0
110.5	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0
115.5	197.0	96.3	91.8	90.3	89.8	89.8	89.7	89.7	89.6	89.8
120.5	91.0	95.7	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0

Figure 6

effect can give an intensity from 10 to 10^3 times the intensity without this focusing effect.

Source depths, receiver depths, and sound frequencies were determined through operational considerations. Source depths of 20 feet, 60 feet, and mixed layer depth plus 100 feet; and receiver depths of 20 feet, 90 feet, and 300 feet were used. Frequencies used were 100 Hz, 3.5 kHz, and 10.0 kHz.

Sea state was evaluated for states two, four, and six, while salinity was assumed constant at 34.70‰. This value was chosen since it is the average surface salinity for the Pacific Ocean according to Muromtsev (1963).

The study was confined to the Pacific Ocean and a "slow" or "P" bottom type was used. The bottom roughness coefficient used was four, since that type bottom occurs most frequently in the Pacific Ocean. A bottom depth of 4000 meters was chosen since this approximates the depth of much of the water close to the western coast of the United States. Data were also obtained for depths of 5000 meters and 6000 meters; however, these data were not as extensive as those obtained for 4000 meters.

Mixed layer depths were varied between the surface and 300 meters in 100-meter increments. Sea surface temperature was varied between 10C and 25C. This range of values was chosen as representative of most of the Pacific Ocean. Data from Muromtsev (1963) and from personnel working extensively with the Pacific Ocean at the FNWF were used to determine the initial temperature profiles. Since most of the extreme variation in water temperature is observed to occur in the upper 400 meters of the ocean, this layer was used in the model for

strong temperature gradient variations. Sea surface temperatures were divided into three groups or families. These groups were 10 to 15C, 15 to 20C, and 20 to 25C.

To establish the initial temperature profile for input to the sound propagation loss model, the three families were assigned constant profiles from 400 meters to the maximum depth of the water (4000 meters, 5000 meters, or 6000 meters). Examples of each of the three families with zero mixed layer depth are shown in Figures 7 and 8, which give conditions in the upper 1000 meters, and in the entire 4000 meters, respectively. These three families represent broad generalizations of the actual conditions in much of the Pacific Ocean, necessary because of the scope of this study.

Using these three families with three temperatures from each (family 1: 10.0C, 12.5C, 15.0C; family 2: 15.0C, 17.5C, 20.0C; family 3: 20.0C, 22.5C, 25.0C) and four mixed layer depths from 0 to 300 meters in 100-meter increments, thirty-six initial programs were constructed. They were to be evaluated by the computer model using sea states two, four, and six; source depths of 20 feet, 60 feet, and mixed layer depth + 100 feet; receiver depths of 20 feet, 90 feet, and 300 feet; and frequencies of 10.0 kHz, 3.5 kHz, and 100 Hz.

This initial run produced eighty-one pages of data (sample shown on page 22) for each of the thirty-six initial inputs. Upon review of the output, it became obvious that meaningful analysis of 250 data values for 2,916 data pages would not be possible in the time available.

Operational usefulness was the main requirement in determining the limits of this study. The decision was made to pursue the 100 Hz propagation loss profile only. The source depths were reduced to

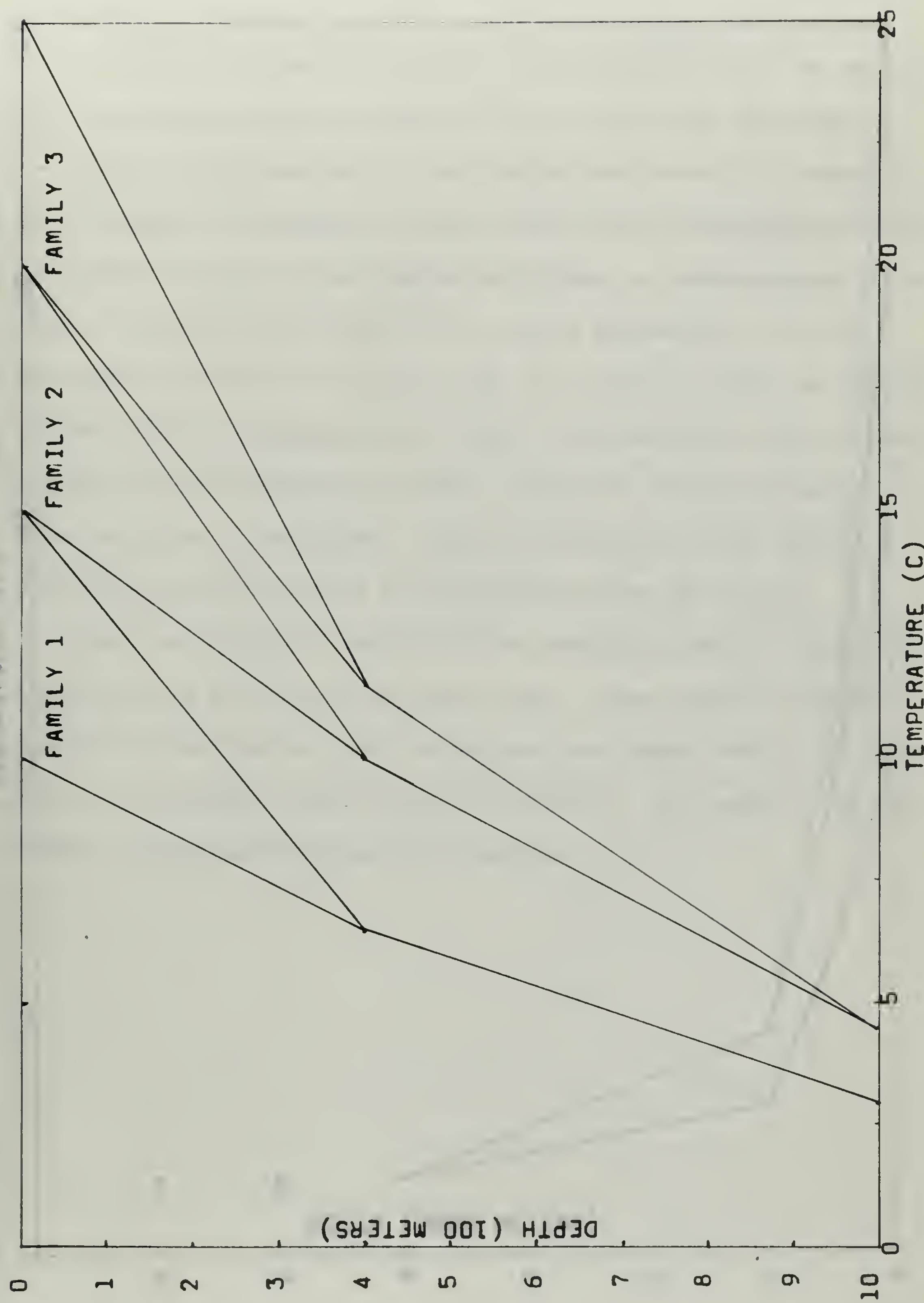


Figure 7

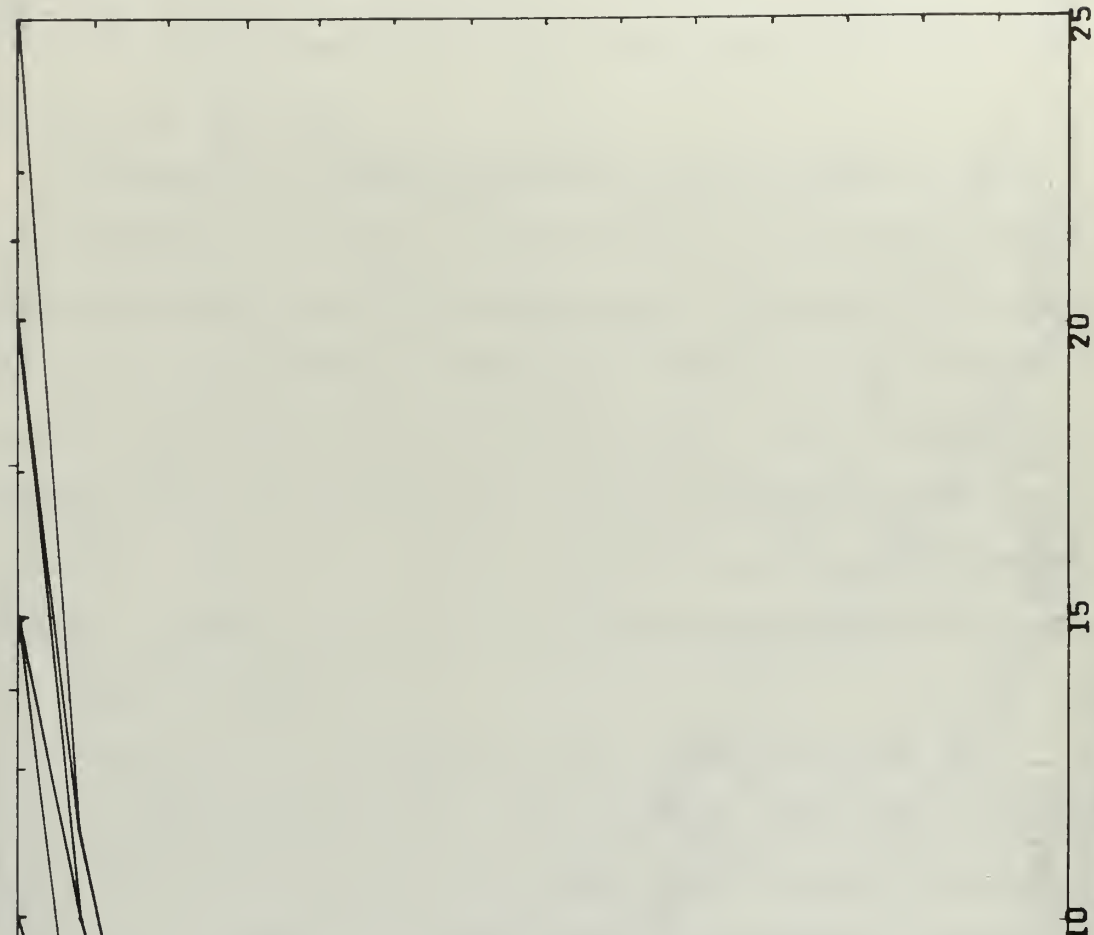


Figure 8

60 feet and mixed layer depth + 100 feet, and the receiver depths were limited to 90 feet and 300 feet. It was decided that sea state four would give adequate information for operational use. The output for each program was thus reduced to four sets of 250 data points.

More thorough analysis of the initial data showed the necessity for additional refinement; it became obvious that more variation would be required in sea surface temperature values to obtain meaningful results. Therefore, intermediate sea surface temperatures and their associated profiles for 11C, 12C, 13C, 14C, 16C, 17C, 18C, and 19C were entered into the propagation loss model. No convergence zones appeared for sea surface temperatures greater than about 18C at 4000-meter water depth and so additional computer runs were made for depths of 5000 meters and 6000 meters for temperatures from 20 to 25C.

Data were developed for the 100-Hz receiver at 90 feet depth with a source at 60 feet and at sea state four. These data were examined closely for information about convergence zone range, width, and intensity for convergence zones one, two, and three. The range to the 100-decibel propagation loss was also examined.

CHAPTER IV

PROPAGATION LOSS FOR OPERATIONAL USAGE

The formulas and graphical representations of the data were developed to give the clearest and most concise display for operational employment. They can be used easily with operator input of sea surface temperature, mixed layer depth, and water depth.

Convergence Zone Range

The first parameter to be examined was the range to the convergence zones. Preliminary review indicated the most promising avenue of approach related the convergence zone range to sea surface temperature and mixed layer depth. Water depth was varied over a sufficient range to achieve convergence zone development for sea surface temperatures up to 25C.

Data were developed for mixed layer depths of 0 to 300 meters at 100-meter increments for the temperature limits of 10C and 25C. Due to computer time required for each run and data reduction time, effort was concentrated on the 100-meter mixed layer depth for temperatures except 10 to 15C where computations were carried out for all four mixed layer depths and one-degree temperature increments.

Using the data obtained, graphs were plotted covering the temperature band from 10 to 25C for mixed layer depth of 100 meters and for all four mixed layer depths from 10 to 15C. A simple equation for convergence zone range prediction was developed from these data. The development method is shown in the Appendix. This equation uses the direct relationship of convergence zone range to sea surface temperature and mixed layer depth to predict range to the first, second, and third convergence zones.

$$R = \left[22.70 + 0.55(T - 10)\right] Z$$

$$+ \left[(T - 9)(0.25Z^{1.32}) - (Z - 1)^{0.8}(0.5)\right] \frac{M - 100}{300} \qquad (4)$$

where

R = range to the start of the convergence zone (nautical miles)

T = sea surface temperature (degrees C)

Z = convergence zone number

M = mixed layer depth (meters).

The errors produced by the formula are very small compared with the width of the convergence zone (see Tables 4, 5, and 6 in Appendix). The average standard deviation of this equation for convergence zones one, two, and three at mixed layer depth of 100 meters is 0.61 nautical miles. The variance and standard deviation for each of the three convergence zones is given in Table 1.

RANGE PREDICTION ACCURACY

	Variance (NM)	Standard deviation (NM)
ZONE 1	0.608	0.786
ZONE 2	0.234	0.483
ZONE 3	0.314	0.560

TABLE 1

Convergence Zone Width

Width of the convergence zones did not lend itself to any easily-predicted formula or organized tabulation of meaningful results when compared with mixed layer depth or sea surface temperature. The

greatest pattern appeared to be within each group of convergence zones. As shown in Table 3, the width of the second convergence zone was usually about twice the first and the width of the third convergence zone was about three times the first. The width of the first convergence zone seemed generally to vary between two and four nautical miles; a few exceptions were as low as one nautical mile and as high as six nautical miles. The second and third convergence zones followed the pattern mentioned earlier and were between four and eight nautical miles and six and twelve nautical miles respectively. The percentage distribution of these data is given in Table 2, for thirty-six observations of each convergence zone.

CONVERGENCE ZONE WIDTH

			MINIMUM	MAXIMUM
ZONE 1 WIDTH (NM)				
2.0-4.0 64.0%	<2.0 14.0%	>4.0 22.0%	1.0	6.0
ZONE 2 WIDTH (NM)				
4.0-8.0 55.5%	<4.0 28.0%	>8.0 16.5%	1.5	10.5
ZONE 3 WIDTH (NM)				
6.0-12.0 58.5%	<6.0 30.5%	>12.0 11.0%	2.0	14.0

TABLE 2

This distribution should enable the operator to make a reasonable estimate of the zone width.

Convergence Zone Intensity

Convergence zone intensity did not lend inself to direct correlation between mixed layer depth, sea surface temperature, or water depth.

CONVERGENCE ZONE WIDTH (NM)

DEPTH 4000m — TEMP (C)

MLD	ZONE	10	11	12	13	14	15	16	17
000	1					5.5	4.5		6.0
	2					10.0	9.0		10.5
	3					14.0	4.5		13.0
100	1		3.0	4.0	2.0	2.0	3.5	1.0	2.0
	2		5.0	7.5	3.0	4.0	6.5	2.5	3.5
	3		7.0	10.5	4.5	6.0	10.0	2.5	5.5
200	1		5.0	4.0		3.5	4.0	3.0	2.0
	2		10.0	8.0		6.5	7.5	6.0	3.0
	3		6.0	10.0		9.5	11.0	8.5	4.0
300	1		2.0	3.5	1.0	1.5	3.5		
	2		4.0	6.5	1.5	3.0	6.5		
	3		6.0	9.5	2.0	4.5	10.0		

DEPTH 5000m — TEMP (C)

MLD	ZONE	10	11	12	13	14	15	16	17
100	1	5.0		3.0				2.5	
	2	9.5		5.5				4.5	
	3	12.5		8.0				6.0	

DEPTH 6000m — TEMP (C)

MLD	ZONE	10	11	12	13	14	15	16	17
100	1			3.5					
	2			6.5					
	3			9.5					

DEPTH 5000m — TEMP (C)

MLD	ZONE	18	19	20	21	22	23	24	25
100	1	5.5		2.5	4.0	1.0	1.0	3.5	
	2	3.5		5.0	7.0	3.0	1.5	6.5	
	3	4.5		6.5	10.5	4.5	2.0	10.0	

DEPTH 6000m — TEMP (C)

MLD	ZONE	18	19	20	21	22	23	24	25
100	1	3.5				2.5	3.0	4.5	6.0
	2	6.5				4.5	6.5	8.5	3.0
	3	9.5				6.5	9.0	12.5	4.0

TABLE 3

Using Figure 9 the operator in the field can immediately assess his opportunity of obtaining a target with a source level less than 85 decibels, between 85 decibels and 95 decibels, and greater than 95 decibels for each of the first three convergence zones. The break points between various decibel levels were determined for operational usefulness and have no other distinct meaning.

The fact that no easily-formulated relationships could be determined from the data obtained for convergence zone width and intensity does not reduce the importance of the work. It indicates the apparent complexity of the convergence zone width and intensity as related to sea surface temperature, mixed layer depth, and water depth. However, the results obtained are still extremely useful to indicate probability of gaining contact by the operator in the field.

100-Decibel Propagation Loss Level

The last parameter covered is the range to the 100-decibel propagation loss level. This range was chosen as being representative of the capability of a low-frequency passive system.

This range was found to vary with water depth, mixed layer depth, and sea surface temperature. The graphical representation can be seen in Figures 10 and 11 (note change in scale for range between Figure 10 and Figure 11). These figures show the variation of range with sea surface temperature and mixed layer depth and with sea surface temperature and water depth.

The 100-decibel loss range can be determined using the following formula:

$$R_{100} = 13.25 - 0.12 \frac{D - 4000}{1000} (T - 10) + (I) \text{ or } (II) \qquad (5)$$

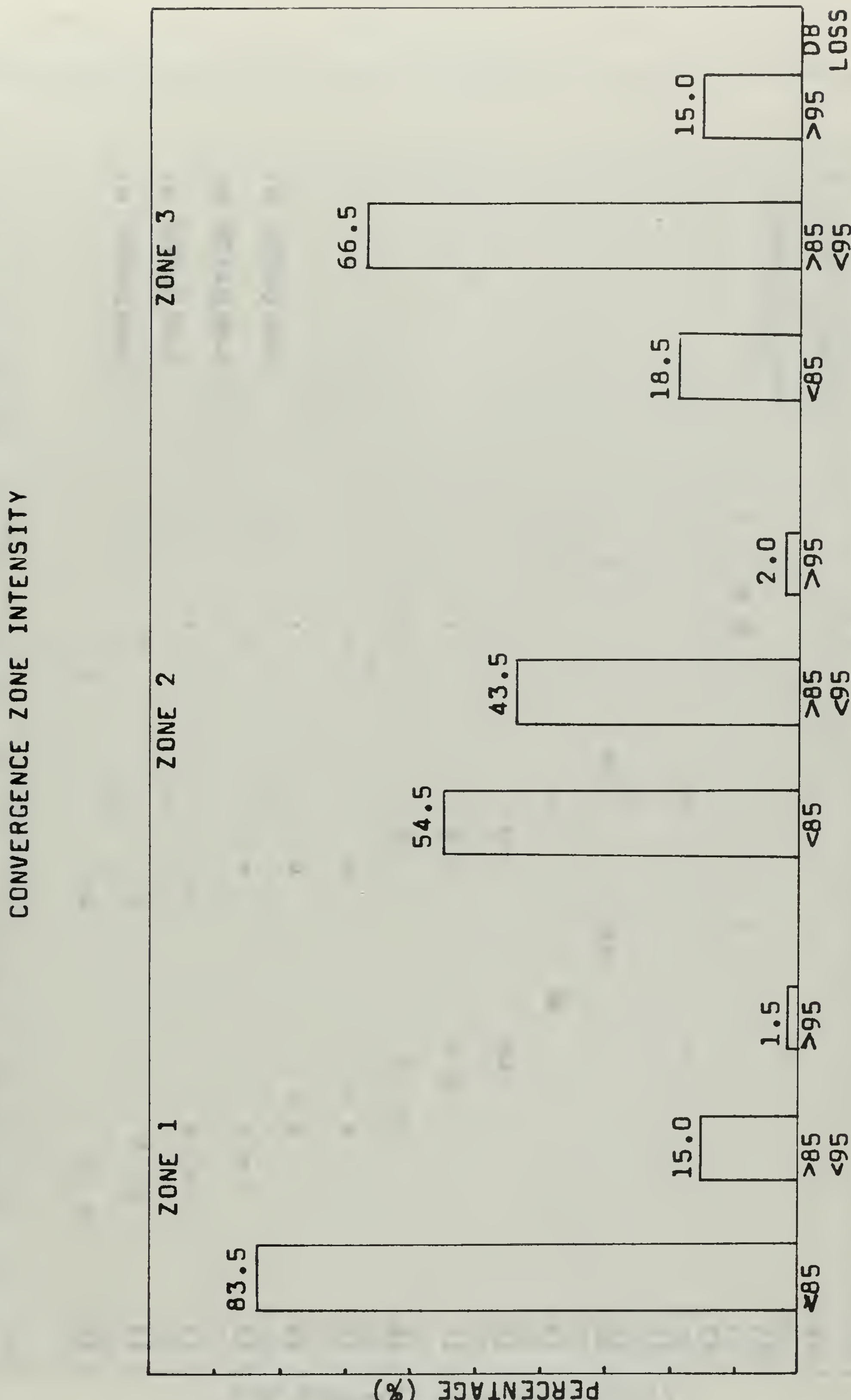
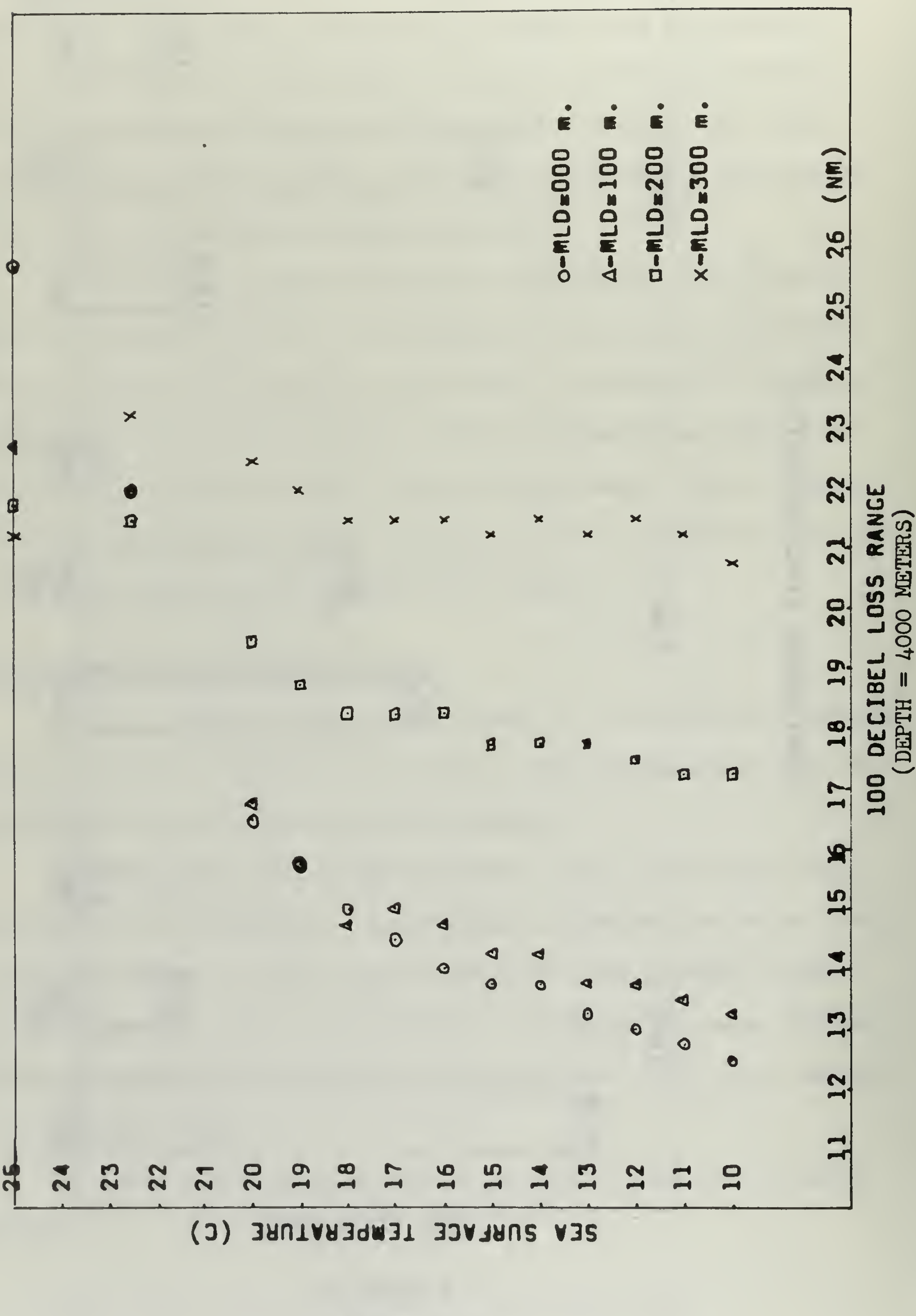
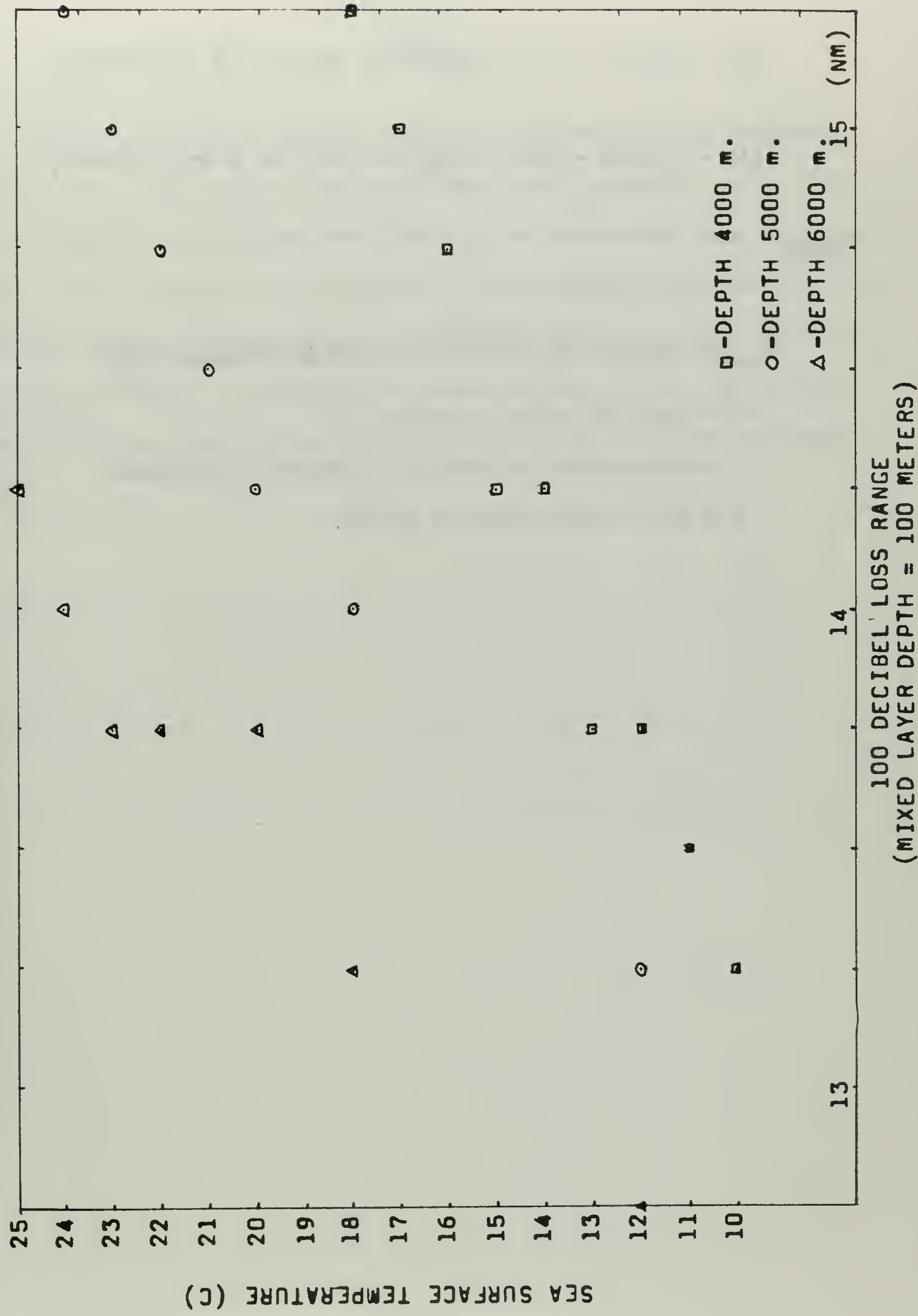

CONVERGENCE ZONE INTENSITY
ZONE 1
ZONE 2
ZONE 3
83.5
15.0
1.5
54.5
43.5
2.0
18.5
66.5
15.0
<85
>85
<95
>95
<85
>85
<95
>95
<85
>85
<95
>95
DB
LOSS
PERCENTAGE (%)

Figure 9



SEA SURFACE TEMPERATURE (C)
100 DECIBEL LOSS RANGE
(DEPTH = 4000 METERS)
(NM)
o-MLD=000 m.
Δ-MLD=100 m.
□-MLD=200 m.
X-MLD=300 m.

Figure 10



□-DEPTH 4000 m.
○-DEPTH 5000 m.
Δ-DEPTH 6000 m.
100 DECIBEL LOSS RANGE
(MIXED LAYER DEPTH = 100 METERS)
(NM)
13
14
15
SEA SURFACE TEMPERATURE (C)
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

Figure 11

$$(I) = 0.25(T - 10) + \frac{M - 100}{100}(0.75) \text{ for } M \leq 100 \text{ meters;}$$

$$(II) = 0.155(T - 10) + \frac{M - 100}{100}(4.00) \text{ for } M > 100 \text{ meters;}$$

where

R_{100} = distance to 100-decibel loss in nautical miles

D = depth of water in meters

T = sea surface temperature in degrees Centigrade

M = mixed layer depth in meters.

CHAPTER V

CONCLUSIONS

Equation (4) was developed to predict the range to the starting point of the first three convergence zones and is accurate within 1500 yards. Used in conjunction with Table 2 for convergence zone width and Figure 9 for convergence zone intensity, the operator can establish the location, width, and intensity of convergence zones one, two, and three. The field operator can obtain an accurate estimate of the 100-decibel propagation loss range by use of equation (5) where convergence zones form.

CHAPTER VI

RECOMMENDATIONS

The convergence zone range should be examined more thoroughly for mixed layer depths between the surface and 100 meters. A more detailed examination over more shallow layer depths should permit refinement of the present formula for greater accuracy.

Convergence zone width and convergence zone intensity should be investigated using a different method than the approach presented in this paper. A constant temperature profile might be maintained and the frequency of the source might be varied over a broad range of frequencies to find a relationship.

The 100-decibel propagation loss range should be investigated using the excess depth below the convergence zone as a reference. More temperature profiles should be processed to refine the prediction formula at mixed layer depths other than 100 meters and for water depths other than 4000 meters.

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APPENDIX

Convergence zone range formula

$$R = \left[22.70 + 0.55(T - 10)\right] Z$$

$$+ \left[(T - 9)(0.25Z^{1.32}) - (Z - 1)^{0.8}(0.5)\right] \frac{M - 100}{300}$$

This formula was developed in two parts. The first part related convergence zone range to sea surface temperature at the fixed mixed layer depth of one hundred meters.

Using the least squares method a first-degree polynomial was fitted to the data for zone one, zone two, and zone three. The results of this fit gave the following polynomials:

ZONE 1 $\quad 22.70 + 0.55(T - 10)$

ZONE 2 $\quad 45.39 + 1.102(T - 10)$

ZONE 3 $\quad 68.07 + 1.644(T - 10)$

These three polynomials were then reduced to the polynomial:

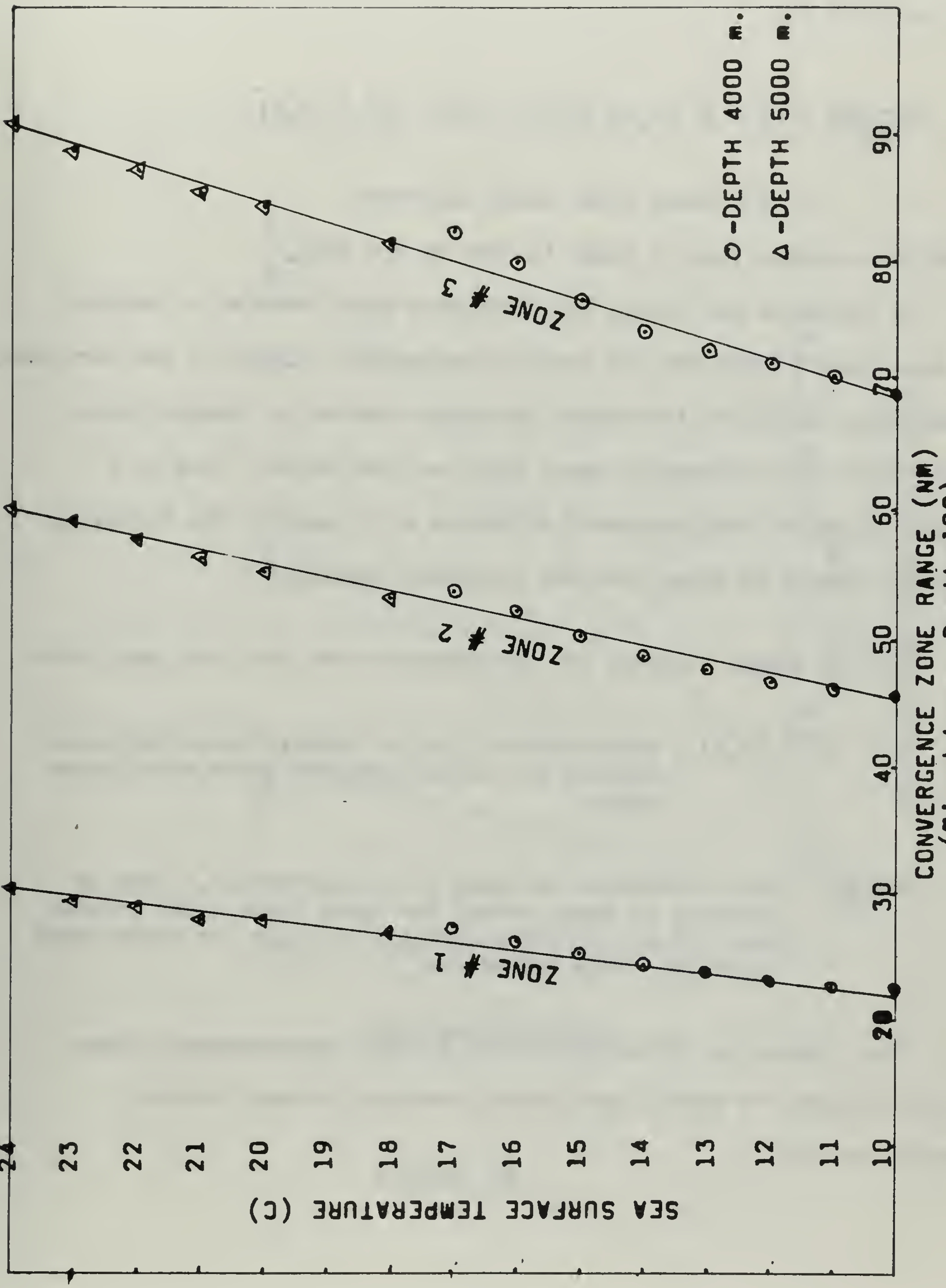
$$\left[22.70 + 0.55(T - 10)\right] Z$$

T = sea surface temperature in degrees Centigrade

Z = convergence zone number one, two, or three

A plot of the actual data with the least squares curve fitted to it is given in Figure 12. As sea surface temperature increases it is necessary to consider deeper water depths in order for a convergence zone to form.

To develop the second part of the formula the first part was used as a standard. Then the change was calculated as a positive or



ZONE # 1
ZONE # 2
ZONE # 3
O-DEPTH 4000 m.
Δ-DEPTH 5000 m.
CONVERGENCE ZONE RANGE (NM)
(Mixed Layer Depth=100)
20 30 40 50 60 70 80 90
SEA SURFACE TEMPERATURE (C)
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Figure 12

negative range as mixed layer depth increased or decreased from one hundred meters. This correction for the change in mixed layer depth is expressed by:

$$\frac{M - 100}{300}\left[(T - 9)(0.25\ Z^{1.32}) - (Z - 1)^{0.8}(0.5)\right]$$

M = mixed layer depth in meters

(Note this entire term is equal to zero at M = 100).

To represent the change in convergence zone range as a function of mixed layer depth and sea surface temperature, Figure 13 was developed. This figure shows the increasing divergence caused by changing mixed layer depth for convergence zones one, two, and three. This is a reduction of the data presented in Tables 4, 5, and 6. The following features should be noted from the graphical display:

$Z^{1.32}$ - change in slope for convergence zones one, two, and three

$(Z - 1)^{0.8}(0.5)$ - term corrects for the initial range difference between the surface and 300 meter mixed layer depth

$\frac{M - 100}{300}$ - term determines the sign of the correction. Thus an increase in range occurs for mixed layer depth greater than 100 meters and a decrease in range for mixed layer depth less than 100 meters.

This formula is effective for sea surface temperatures between 10 and 25C and for mixed layer depths from the surface to three hundred meters.

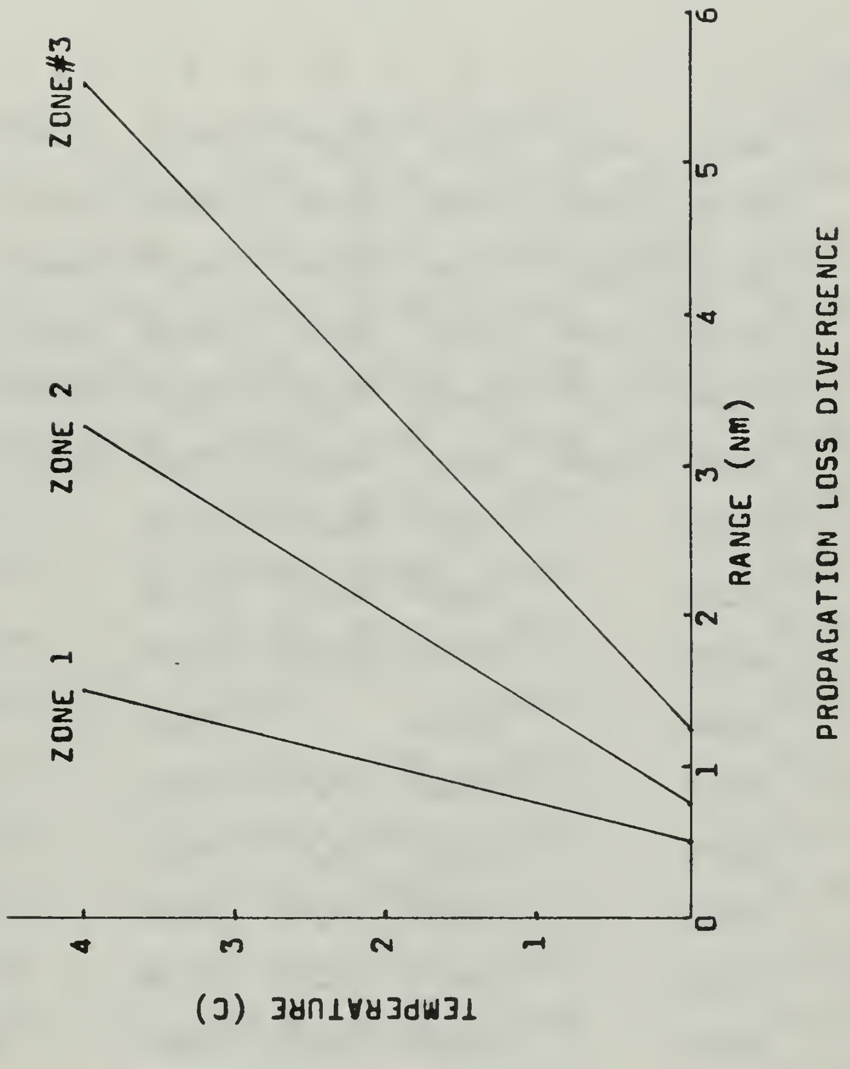

ZONE 1
ZONE 2
ZONE#3
TEMPERATURE (C)
0
1
2
3
4
5
6
RANGE (NM)
PROPAGATION LOSS DIVERGENCE

Figure 13

PREDICTED AND ACTUAL RANGE OF CONVERGENCE ZONE ONE

P = predicted range (nautical miles)

A = actual range (nautical miles)

	MLD = 000m		MLD = 100m		MLD = 200m		MLD = 300m	
T (C)	P	A	P	A	P	A	P	A
10	22.62	22.50	22.70	23.00	22.78	23.00	22.86	23.00
11	23.08	23.00	23.25	23.00	22.92	23.50	23.59	23.50
12	23.55	23.00	23.80	23.50	24.05	24.00	24.30	24.00
13	24.02	23.50	24.35	24.00	24.68	24.50	25.01	24.50
14	24.48	24.00	24.90	24.50	25.32	25.00	25.74	25.50
15	24.95	24.50	25.45	25.50	25.95	25.50	26.45	26.00
16	25.42		26.00	26.50	26.58		27.16	
17	25.88		26.55	27.50	27.22		27.89	
18	26.35		27.10	27.00	27.85		28.60	
19	26.82		27.65		28.48		29.31	
20	27.28		28.20	28.00	29.12		30.04	
21	27.75		28.75	28.00	29.75		30.75	
22	28.22		29.30	29.00	30.38		31.46	
23	28.68		29.85	29.50	31.02		31.19	
24	29.15		30.40	30.50	31.65		32.90	
25	29.62		30.92		32.33		33.61	

TABLE 4

PREDICTED AND ACTUAL RANGE OF CONVERGENCE ZONE TWO

P = predicted range (nautical miles)

A = actual range (nautical miles)

T (C)	MLD = 000m P	MLD = 000m A	MLD = 100m P	MLD = 100m A	MLD = 200m P	MLD = 200m A	MLD = 300m P	MLD = 300m A
10	45.36		45.40	46.00	45.44		45.48	
11	46.25	46.00	46.50	46.50	46.75	46.50	47.00	46.50
12	47.14	46.50	47.60	47.00	48.06	48.00	49.52	48.00
13	48.03	47.00	48.70	48.00	49.37	48.50	50.03	49.50
14	48.92	48.00	49.80	49.00	50.58	50.00	51.45	50.50
15	49.82	49.00	50.90	50.50	51.98	51.50	53.06	52.50
16	50.71		52.00	52.50	53.29		54.58	
17	51.60		53.10	54.00	54.60		56.10	
18	52.49		54.20	53.50	55.91		57.62	
19	53.38		55.30		57.22		59.14	
20	54.18		56.40	55.50	58.52		60.64	
21	55.17		57.50	56.50	59.83		62.16	
22	56.06		58.60	58.00	61.14		63.68	
23	56.95		59.70	59.50	62.45		65.20	
24	57.84		60.80	61.00	63.76		66.72	
25	58.73		61.90		65.07		68.24	

TABLE 5

PREDICTED AND ACTUAL RANGE OF CONVERGENCE ZONE THREE

P = predicted range (nautical miles)

A = actual range (nautical miles)

	MLD = 000m		MLD = 100m		MLD = 200m		MLD = 300m	
T (C)	P	A	P	A	P	A	P	A
10	68.04		68.10	68.50	68.16		68.23	
11	69.33	69.00	69.75	70.00	70.17	70.00	70.58	70.00
12	70.63	69.50	71.40	71.00	72.17	72.00	72.91	72.00
13	71.93	70.50	73.05	72.00	74.17	73.00	75.29	74.00
14	73.23	72.00	74.70	73.50	76.17	75.00	77.64	76.00
15	74.52	73.00	76.35	76.00	78.18	78.00	80.01	78.50
16	75.82		78.00	79.00	80.18		82.36	
17	77.11		79.65	81.50	82.19		84.73	
18	78.41		81.30	80.50	84.19		87.08	
19	79.71		82.95		86.19		89.43	
20	81.00		84.60	83.50	88.20		91.80	
21	82.31		86.25	84.50	90.19		94.13	
22	83.60		87.90	87.00	92.20		96.50	
23	84.90		89.55	89.00	94.20		98.85	
24	86.19		91.20	91.50	96.21		101.22	
25	87.49		92.85		98.21		113.57	

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1. ORIGINATING ACTIVITY *(Corporate author)* Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Sound Propagation Loss Prediction for 100 Hz Receiver

4. DESCRIPTIVE NOTES *(Type of report and, inclusive dates)*

Thesis

5. AUTHOR(S) *(First name, middle initial, last name)*

LT Walter L. Glenn, Jr.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1968	48	8

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
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13. ABSTRACT

This paper reports an attempt to simplify for ease in field use the complex numerical model for sound propagation loss prediction developed by Dr. C. S. Clay, Captain P. M. Wolff, and Dr. P. R. Tatro (LCDR, USN). Due to time required for communications and computation, the present results of this model are not available for immediate use by the operator in the field.

This computerized model was used to analyze propagation loss for temperature profiles with sea surface temperature varying between 10C and 25C and variation in mixed layer depth from the surface to 300 meters. From these data formulas and graphs were developed to predict convergence zone range, width, and intensity and the 100-decibel propagation loss range. These results are intended for operational use by field personnel.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6811

Unclassified

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